

Shallow Gas Studies of the Gulf of Lions, Including the Rhône Delta and Cap de Creus Canyon Head

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Contract Number: N00014-03-1-0142
<http://www.soc.soton.ac.uk/CHD/EUROSTRATAFORM/index.html>

LONG-TERM GOALS

To enhance and expand our understanding of the inter-relationship of shallow gas, seafloor morphology, and seafloor/shallow sub-surface acoustic properties. To continue our successful collaboration with our EuroSTRATAFORM colleagues through Gulf of Lions (GoL) post-cruises analysis, interpretation, and integration with geophysical data sets. The main Institutions we have collaborated with are: CEREGE, France; U.S. Geological Survey, USA; ISMAR-CNR, Italy; Fugro Surveys Ltd., UK; and Univ. Laval, Canada.

To compare the Gulf of Lion (GoL) system with other areas worldwide and augment including an industry data set from the eastern Mediterranean. Our two main topics of interest are the distribution and effects of shallow gas on both the seafloor and the shallow sub-surface, and the origin and evolution of “crenulated seafloor” (wavy bedforms, slope failure features, or a combination of the two) and seafloor rills.

OBJECTIVES

To understand how shallow gas and flood events are inter-related in the GoL system through the integration of mapping and coring. Previous ONR work in the Adriatic (2003-2004) showed that the Po flood deposits resulted in a localized region of high organic matter deposition, and that the rapid accumulation of flood deposits removed the organic matter from the reach of physical and biological re-working, leading to high concentrations of shallow gas. Our goal in the GoL was to determine if this model also holds for the Rhone system, which experienced a large flood in December, 2003.

Specific detailed sites of interest in the GoL include the Grand Rhône prodelta (inferred to be the main source for organic matter and therefore potential gas), along the western coast of the GoL (the circulation patterns, satellite and shuttle images as well as models indicate that this is the main pathway for flood-derived material) and in the Cap de Creus canyon, where flood sediments may be transported off the shelf (see Figure 1).

We were also interested in interpreting the available geophysical data that suggested anomalies due to gas-prone sediments, with follow-up coring to groundtruth that data through headspace analyses of gas. Our analyses of gas in the cores are combined with our colleague's work on organic matter (ISMAR-CNR, Italy), sediment accumulation rates (CEREGE, U. Washington and TAMU), modeling (IFREMER, Duke U.) and current measurements and circulation (CSIC, Spain; U. Perpignan, France).

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2006		2. REPORT TYPE		3. DATES COVERED 00-00-2006 to 00-00-2006	
4. TITLE AND SUBTITLE Shallow Gas Studies of the Gulf of Lions, Including the Rhone Delta and Cap de Creus Canyon Head				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California,Earth Sciences Department,Santa Cruz,CA,95064				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

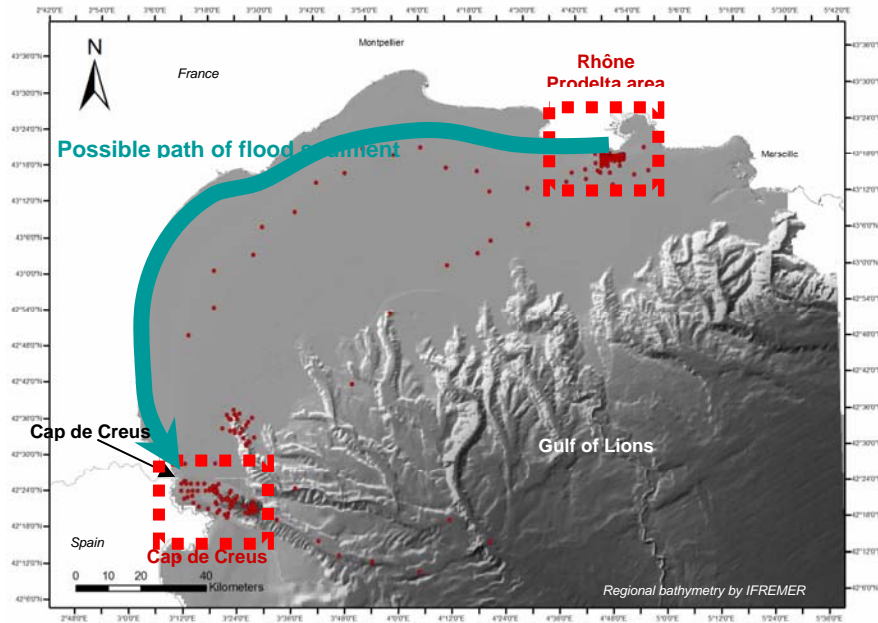


Figure 1. Cores taken for headspace gas analyses in several cruises during 2004 and 2005. Most of our work has been focused on the Rhône prodelta and Cap de Creus areas.

APPROACH

Remote sensing and modeling suggested that from the Rhône area the flood sediment is carried southwest along the shelf, and that the canyons in the southwest GoL, including the Cap de Creus (CdC) canyon, act as primary escape routes for the flood sediment. To evaluate the link between flood sediment and shallow gas formation, we analyzed cores from the Rhône prodelta, and compared our results with the analyses of sediment accumulation related to the recent flood. Our gas analyses were also compared with other EuroSTRATAFORM workers who are studying the organic matter and floc fractions.

In the GoL study area, our research addresses seafloor acoustic properties, sub-seafloor acoustic anomalies, and shallow gas. Our primary approach utilizes multibeam bathymetry and backscatter, sub-bottom profiling, and headspace analysis of sediment cores. Our collaboration with EuroSTRATAFORM scientists enhances our work by providing significant data that provides additional insight into the processes that impact seafloor morphology and acoustic properties. Dr. Stefano Misserocchi at ISMAR-CNR (Bologna, Italy) provides organic matter analyses in the same cores we analyze for headspace gas. Dr. Chuck Nittrouer (U. Washington) and Dr. Beth Mullenbach (TAMU) determine sediment accumulation rates in many of the cores we analyze. In the Rhône prodelta area, Dr. Olivier Radakovitch at CEREGE and Dr. Serge Berne at IFREMER provide valuable data and models for sediment accumulation, seafloor morphology, and sub-bottom data that provide a context for our core analyses. Dr. Patrick Friend (University of Southampton) provided a geomorphological study through ADCP profiles off the Rhone area that positively correlate with our shallow gas findings (Figure 2). In the Cap de Creus area, high-resolution multibeam mapping and sub-bottom profiler data of the upper canyon provided the basis for coring studies. Gas analyses were

carried out on most of the cores acquired in the GoL as part of the EuroSTRATAFORM program, including most of the cores acquired primarily for other research objectives by other PIs. All gas composition and isotope analyses have been carried at the U.S. Geological Survey under the direction of Dr. Tom Lorenson at no charge to ONR.

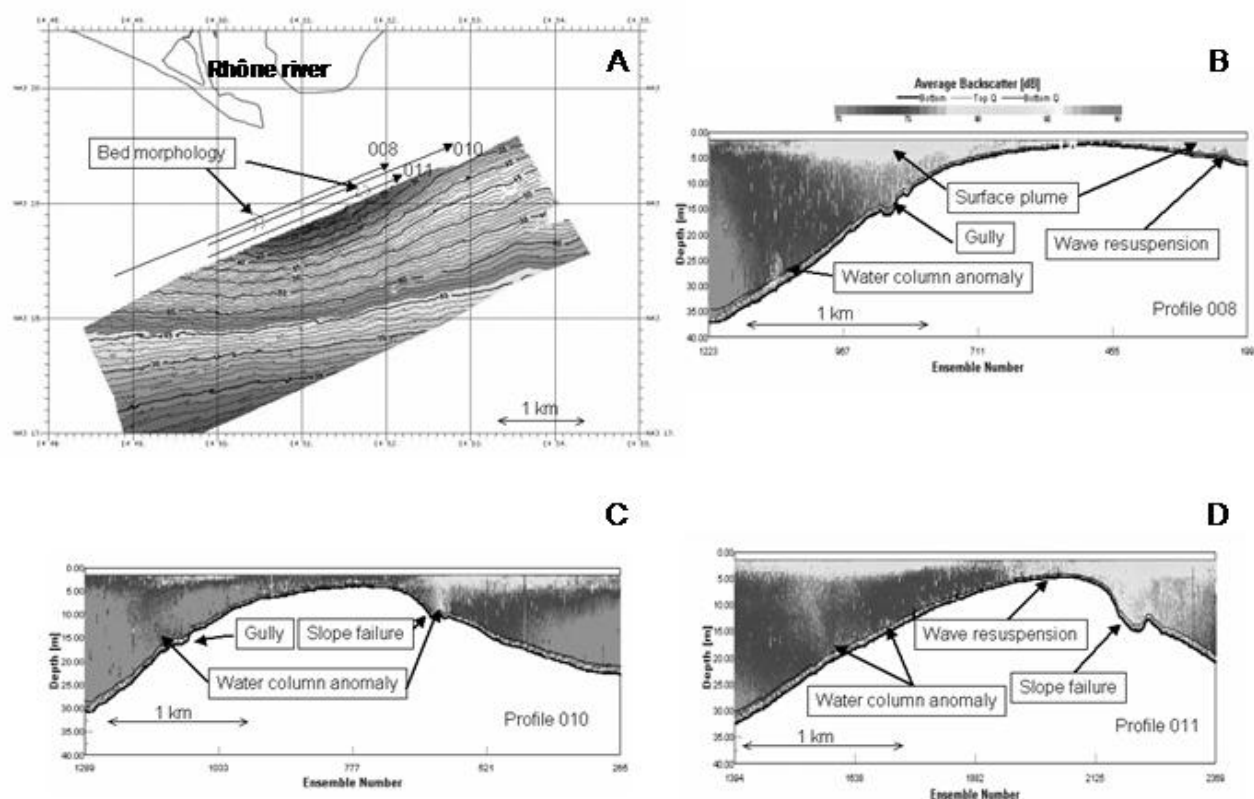


Figure 2. (A) tracks and track directions of backscatter ADCP profiles acquired off the Rhône mouth, November 2003. The general morphology of the slump features is outlined; (B) profile 8; (C) profile 10; and (D) profile 11. The positions of anomalies in the water column close to the sea bed are indicated, together with the position of the surface hyperpycnal plume. Areas of high backscatter on the delta top are probably caused by wave resuspension. Bed features were interpreted during a geomorphological study of the delta front.

WORK COMPLETED

Grand-Rhône prodelta:

Working with our EuroSTRATAFORM colleagues, we identified a large number of coring sites on the Rhône prodelta, which were cored in March and October 2004. A total of 77 sites were analyzed for gas content (methane through hexane, C1-C6), CO₂, and H₂S by gas chromatography. Sites included areas of interpreted sediment accumulation related to the recent flooding, as well as sites where ADCP data suggested gas seepage out of the seafloor (Dr. Patrick Friend, SOC, UK)-see figure 2. A subsequent analysis of the change in bathymetry related to the flood deposit was carried out by Dr. Serge Berne, IFREMER, France, and compared to the sampled sites. An additional 12 sites were

analyzed during two additional cruises to the Rhône prodelta in February and May, 2005. All geochemistry analyses on the GoL cores have been completed, and are included in a paper currently in press.

The Cap de Creus canyon head:

In March, 2004 AOA Geophysics Inc. and Fugro Survey Ltd. acquired a high-resolution map of the Cap de Creuse canyon head at no charge to ONR. These data, which include multibeam bathymetry, multibeam backscatter, and sub-bottom profiler data in a GIS environment (plus Fledermaus fly-throughs) have been circulated on a DVD to colleagues. These DVDs have been made available to all EuroSTRATAFORM scientists, and serve as a basemap for anyone working in the CdC area. We have distributed more than 80 additional DVDs to the scientific community to date.

Again, working with our EuroSTRATAFORM colleagues, we identified a large number of coring sites in the Cap de Creus canyon, which were cored in October 2004. A total of 56 sites were analyzed for gas content (methane through hexane, C1-C6), CO₂, and H₂S by gas chromatography. Sites include transects both across canyon and down-canyon. Sites were selected to target morphological regions identified on the bathymetric data, as well as sites where the sub-bottom profiler data suggested potential gas. An additional 88 sites were analyzed during two additional cruises to the Cap de Creus canyon in February and May, 2005. All geochemistry analyses on the Cap de Creus cores have been completed, and are included in a paper submitted for publication.

RESULTS

Grand-Rhône prodelta:

A total of 92% of the 89 Rhône cores show anomalous concentrations of methane (up to 87440 ppm). Compositional and isotopic analyses of the gas support a microbial origin although there are a few sites that show relatively heavy $\delta^{13}\text{C}$ values (-53 per mil) suggesting a mixed source for the gas. Anomalous methane concentrations have been evaluated and integrated with organic carbon data, sedimentary rates and ADCP profiles. All of the highest gas concentrations of gas were found directly off the river mouth where the models and mapping indicate the thickest accumulation (> 2 m) of sediment related to the flood event. Sampled sites include locations where previous surveys identified acoustic anomalies in high-resolution seismic profiles which may be related to the presence of gas. We propose that, similar to the Po prodelta in the Adriatic, in the Rhône prodelta flood deposits deliver significant amounts of terrigenous organic matter that can be rapidly buried, effectively removing this organic matter from aerobic oxidation and biological uptake, and leading to the potential for methanogenesis with burial. In areas unaffected by this high flux of organic matter and rapid/thick flood deposition, or in between flood events, the conditions for methanogenesis and gas accumulation have not been met. In these areas, the physical and biological reworking of the surficial sediment may effectively oxidize and mineralize organic matter and limit bacterial methanogenesis in the subsurface.

Gulf of Lions:

Besides the specific detailed sites of interest in the GoL (Grand Rhône prodelta and Cap de Creus canyon-see below), a regional approach on understanding the pathways for organic matter/source of shallow gas along the western coast of the GoL was undertaken. Away from the flood-related

sediments off the Rhône delta, where rapid and thick burial of terrigenous organic matter can fuel methanogenesis, we found no evidence of shallow gas despite recent sediment accumulation. We propose that the thickness of the burial deposit is insufficient to protect the organic matter from reworking, and as a result the organic matter is being consumed and/or remineralized on its way along the western coast of the GoL.

The Cap de Creus canyon head:

During July 2004 Fugro Survey Ltd. and AOA Geophysics Inc. mapped the head of the canyon with a hull-mounted Kongsberg 30 kHz EM300 system aboard Fugro's *M/V Geo Prospector*. This mapping was carried out for PR purposes by Fugro and AOA at no charge to ONR. A high-resolution sub-bottom profiler survey was also run in the area simultaneously (see Figure 3). Several EuroSTRATAFORM cruises run between 2004 and 2005 used the Fugro/AOA data as a basemap for evaluating the processes responsible for creating and modifying the canyon morphology and seafloor acoustic properties. Analyses of 79 cores (piston, kasten and box cores) provide information about lithology, sediment accumulation rate, gas content and organic matter. The analyses show relatively little shallow gas in the core samples (only a 4% show anomalous methane signature). Samples with anomalous gas (up to 715 ppm of methane) are limited to the northern flank of the canyon, where the samples also show higher amounts of organic matter and the bathymetry and backscatter suggest recent sediment drape. The southern flank and the canyon axis show no anomalous gas in any of the samples, yet sediment accumulation rate studies indicate relatively high (but spatially variable) rates of accumulation in the canyon axis. Our hypothesis is that away from the flood-related sediments off the Rhône delta the organic matter in these sediments has been reworked and remineralized on its way along the western coast of the Gulf of Lions, so that the recent deposits in the canyon contain little reactive carbon. The anomalous samples on the northern flank may be related to methanogenesis of recent drape or of older sidewall canyon infill.

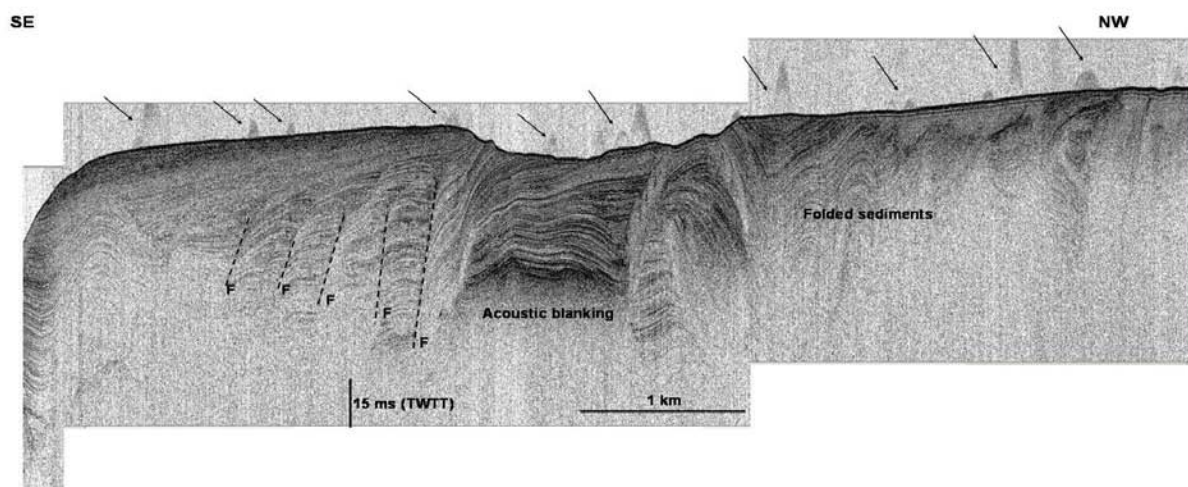


Figure 3. Sub-bottom profiler line 17 (SE-NW) in head of the CdC canyon. Note the common acoustic plumes in the water column, some of them above faults. Sediment below the present seabed is folded and faulted. Note the acoustic blanking below the seafloor in the middle section.

The new high resolution seafloor (bathymetry and backscatter) plus sub-surface (sub-bottom profiler) data provide detailed images of the upper Cap de Creus canyon, off the northeast coast of Spain in the Gulf of Lions (Figure 4). Co-registered multibeam bathymetry and backscatter show the north canyon wall to be relatively smooth and low backscatter. In contrast, the south flank of the canyon shows furrows, outcrops, and anomalously high backscatter. We interpret the north wall of the canyon to be a zone of recent (active?) sediment accumulation and drape, and the south wall of the canyon a zone of sediment bypass or recent (active?) erosion.

High-resolution multibeam data show an unusual region of seafloor 'rills' or 'furrows' within the Cap de Creus canyons. These linear features, up to several kilometers long, 100m apart, and <1m deep, are spatially associated with down-canyon currents driven by cold-water cascading that is in turn forced by met-ocean conditions within the larger Gulf of Lions. By teaming with other EuroSTRATAFORM researchers we have been able to propose the linkage between the oceanographic forcing, observed currents, and these unusual seafloor features, as well as the linkage between sediment accumulation, organic matter, and shallow gas (Figure 4; for a full list of colleagues on this multi-disciplinary effort, please see Orange et al., submitted, below).

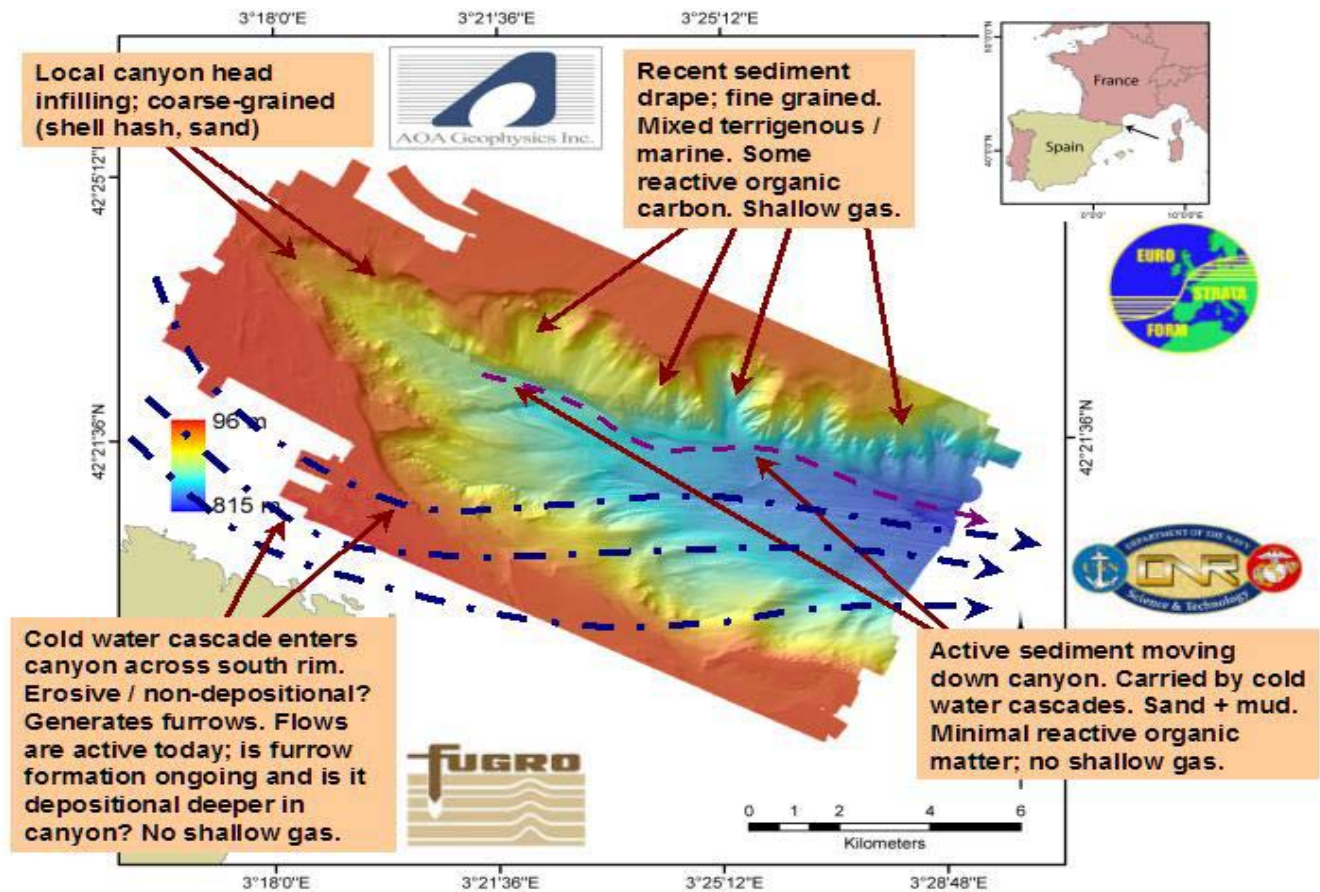


Figure 4. Multibeam bathymetry with shaded relief rendering of the upper Cap de Creus canyon offshore northeastern Spain; see inset for location. The bathymetry, backscatter, and sub-bottom data within the area show distinct signatures that can be tied to processes. Although EuroSTRATAFORM colleagues documented active sediment accumulation within the canyon axis, we found no evidence of shallow gas; we interpret this to be due to the reworking and remineralization of the carbon en route to the canyon, and contrast this with the reactive organic matter deposited with drape sediments on the north wall of the canyon. Of note is the spatial association of imaged seafloor furrows or rills and cold water cascades measured by EuroSTRATAFORM colleagues that enter the canyon rim and travel down canyon for a period in excess of two months at rates peaking at 80 cm/s.

Although there is an inherent disconnect in temporal scales between oceanographic modeling /measurements and process geomorphology and the resultant bedforms, we have proposed a conceptual model linking the two (see Figure 4). Oceanographic modeling and measurements show that the circulation of water masses in the western Gulf of Lions is primarily controlled by winds. Currents on the shelf are funneled southward toward the narrowing end of the shelf, and ultimately encounter the Cap de Creus promontory and canyon. During winter storm events E-SE Bora winds lead to seasonally cold, dense water that, due to the promontory, descends across the south wall and down-canyon with a trend consistent with the imaged furrows on the seafloor. Such cold water cascades have been captured by moorings placed in the canyon that show individual cascade events lasting more than a month with associated current speeds as high as 80 cm/s oriented toward the NNE (i.e.: coming from the south).

wall). These intense cold water cascades were also characterized by large peaks in suspended sediment concentrations, confirming that they are an effective off-shelf transport mechanism. The presence of recent accumulation in the canyon axis, sidewall slumping (which transports material from the sidewalls to the canyon thalweg), and furrows (related to cold-water cascades and measured increases in suspended sediment accumulation) indicates that even today, the Cap de Creus canyon is efficiently transporting sediment from the shelf to the slope.

IMPACT/APPLICATIONS

The Rhône prodelta mapping and sampling program provide data consistent with the model developed as part of our earlier EuroSTRATAFORM work off the Po in the Adriatic. In this model, flood deposits deliver significant amounts of terrigenous organic matter that can be rapidly buried, effectively removing this organic matter from aerobic oxidation and biological uptake, and leading to potential methanogenesis with burial. In areas unaffected by this high flux of organic matter and rapid/thick flood deposition, or in between flood events, the conditions for methanogenesis and gas accumulation have not been met. In these areas, the physical and biological reworking of the surficial sediment may effectively oxidize and mineralize organic matter and limit bacterial methanogenesis in the subsurface. Now that we have shown this model to be consistent for the Po and the Rhône, we suggest that the model can be extrapolated to other flood-related shallow environments worldwide to explain and understand the occurrence and distribution of shallow gas. This model, and its implications for methanogenesis, may provide an important baseline for understanding seafloor acoustic and geotechnical properties, and the potential for gas-related failure of near-surface sediments. This model also has implications for carbon cycling and climate change.

Our mapping program in 2004 in the Cap de Creus area (conducted with AOA Geophysics and Fugro Survey Ltd.) was key to understanding the recent processes in the Cap de Creus canyon, and provided a detailed base map for all of the subsequent EuroSTRATAFORM coring and mapping in the canyon. This image appeared on the cover and back of the special issue of *Oceanography* in December 2004. This special issue highlighted the EuroSTRATAFORM program. More recently several Special Publications in international journals such as *Marine Geology* and *Continental Shelf Research* have been the platform for EuroSTRATAFORM scientists to publish their findings. Several of those are currently in press; the rest will be finally published by early 2007.

In the last year, we have actively participated in five international meetings/workshops: the VIIIth International Conference on Gas in Marine Sediments, Vigo (Spain)-two talks; Fall Meeting American Geophysical Union, San Francisco (USA)-one talk; EuroSTRATAFORM/PROMESS meeting, Salamanca (Spain)-one talk/one poster; a "'Gassy Sediment Workshop" held in Bay St. Louis, Mississippi that resulted in an EOS publication; and a EuroSTRATAFORM meeting/workshop, Charlottesville (USA).

PUBLICATIONS

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Submitted:

García-García, A., Orange, D., Heffernan, A., Maher, N., Fortier, G., Malone, A. (submitted) High-resolution geophysical study of echo types and upslope migrating sedimentary waves: Inner Lakatia basin, East Mediterranean Sea. *Marine Geology*.

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